Fermi National Accelerator Laboratory

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CDF

Search for Excited Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

If quarks are composite particles then excited states are expected. We have searched in $p\bar{p}$ collisions for excited quarks (q^*) which decay to common quarks by emitting a W boson ($q^* \to qW$) or a photon ($q^* \to q\gamma$) . The simplest model of excited quarks has been excluded for mass $M^* < 540$ GeV/c^2 at 95% confidence level.

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Models in which quarks are composite particles have the potential to explain the proliferation of quarks and their replication in three generations. These models usually also predict the existence of excited quarks in which the composite bound state has been excited from the ground state (e.g. u or d quarks) to some excited state (u^* or d^*). In the simplest model [1] excited quarks can be produced in $p\bar{p}$ collisions via quark-gluon fusion, and can decay to a common quark by emitting any gauge boson [2]. Here we search for excited quarks (q^*) decaying to either a quark and a W boson or a quark and a photon.

A detailed description of the Collider Detector at Fermilab (CDF) may be found elsewhere [3]; the components relevant for this analysis are described briefly here. We use a coordinate system with z along the proton beam, azimuthal angle ϕ, polar angle θ, and pseudorapidity $\eta = -\ln\tan(\theta/2)$. A central tracking chamber (CTC) measures charged particle momenta for $|\eta| < 1.2$. Scintillator-based electromagnetic

(EM) and hadronic (HAD) calorimeters in the central region ($|\eta| < 1.1$) are arranged in projective towers of size $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.26$. Gas-based calorimeters cover the plug ($1.1 < |\eta| < 2.4$) and forward ($2.4 < |\eta| < 4.2$) regions. The central electromagnetic strip chambers (CES) are multiwire proportional chambers embedded inside the central EM calorimeter near shower maximum. Outside the central calorimeters, the region $|\eta| < 0.63$ is instrumented with four layers of drift chambers for muon detection.

This analysis used data from both the 1988-89 and 1992-93 running periods, henceforth referred to as the 1989 and 1992 runs. For the photon analysis, during the 1989 (1992) run, photon triggers of total integrated luminosity 3.3 pb^{-1} (21.3 pb^{-1}) were taken with a hardware (software) threshold of 23 GeV (70 GeV) of EM transverse energy. For the W analysis, during the 1989 (1992) run, electron and muon triggers of total integrated luminosity 4.05 pb^{-1} and 3.54 pb^{-1} (21.3 pb^{-1}) were accumulated. To reject jet backgrounds, the photon and electron software triggers required that at least 89% of the transverse energy of the EM cluster be in the EM compartment of the calorimeter. An EM cluster is three EM towers contiguous in η. To maintain the projective nature of the calorimeter towers we required the event z vertex be within 60 cm of the center of the detector.

A photon candidate is an isolated neutral EM cluster well within the CES fiducial region for good position measurement and shower containment. The isolation requirement was that the extra transverse energy inside a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$ surrounding the photon was less than 4 GeV. Charge neutrality was determined by only selecting events with no tracks pointing at the EM cluster, or up to one track with $P_T < 1$ GeV/c. The transverse profile in the CES and additional energy depositions in the CES were required to be compatible with a photon shower in order to reduce the background from decays of π^0 and η mesons. To reject photons from cosmic ray muon bremsstrahlung, we required the missing transverse energy [4] in the detector be less than 80% of the photon transverse energy. The efficiency of all cuts for photons in the measured pseudorapidity interval $|\eta| < 0.9$ varied from 57% at low q^* mass to 47% at high mass including fiducial cuts. The total acceptance for $q^* \to q\gamma$ varied from 34% at low mass to 27% at high mass.

Events with a W boson were found from its decay into electrons or muons with high lepton transverse momentum ($P_T > 20$ GeV/c) and event missing transverse energy [4] ($\not{E}_T > 20$ GeV). The electron (muon) was required to have $|\eta| < 0.95$ ($|\eta| < 0.6$) and be separated from any nearby jets by a distance $R > 0.9$ ($R > 0.25$) in η-ϕ space. Cuts defining an electron and muon were the same as previously published [4, 5]. For both lepton varieties, cosmic ray events were reduced by rejecting events with out-of-time energy deposition, and cuts on the presence of a second lepton were included to reject Z boson events. The efficiency of all cuts for electrons (muons) in the measured pseudorapidity interval varied from 32%(34%) at low q^* mass to 49%(43%) at high mass including fiducial cuts. The total acceptance for $q^* \to qW$ for W decays to an electron (muon) varied with mass from 16%(11%) to 34%(21%).

Events with high P_T photon candidates or W bosons typically contain a recoiling jet of hadrons. The jet energy was defined as the scalar sum of calorimeter tower energies inside a cone of radius $R = 0.7$ centered on its transverse energy centroid, and then corrected to account for calorimeter non-linearities and uninstrumented regions. The jet with the highest transverse energy in the event is called the leading jet, and for the q^* search, it was assumed to correspond to the fragmentation products of the quark coming from the hypothetical q^* decay. For the $q^* \rightarrow qW$ search the jet was required to have greater than 15 GeV transverse energy; at lower energies jet measurement is difficult.

For the $q^* \rightarrow q\gamma$ search, we improved our mass resolution by avoiding the use of the jet energy and assumed that the jet and photon balanced in P_T, as they must for the lowest order process $qg \rightarrow q^* \rightarrow q\gamma$. The photon + jet mass is given by $M = (2P_{T\gamma}/c)\cosh\eta^*$ where $\eta^* = (\eta_\gamma - \eta_{JET})/2$ and we required $P_{T\gamma} > 30$ GeV/c. For the $q^* \rightarrow qW$ search, the z-component of the neutrino momentum $P_{z\nu}$ in the decay $W \rightarrow l\nu$ was constrained to give a $l\nu$ mass equal to the W boson mass. Events that could not be constrained to the W mass were constrained to the transverse mass of the W in the event (25% of the events). The constraint resulted in two solutions for both $P_{z\nu}$ and the W + jet mass. We picked the smaller mass solution in order to present a conservative mass distribution. The experimental mass resolution for the $q^* \rightarrow q\gamma$ ($q^* \rightarrow qW$) search was roughly an RMS deviation of 5% (13%) which dominated over the predicted half width at half maximum of the q^* resonance, which was $\Gamma/2 = 2\%$ [1].

Excited quark decays are isotropic producing an angular distribution that is flat in $\cos\theta^*$, while the QCD background is strongly peaked at high $|\cos\theta^*|$ from t-channel production. Here θ^* is the angle between the jet and the proton beam in the center of momentum frame of the collision products. To reduce QCD backgrounds, and also to have well understood acceptance as a function of mass, the $q^* \to q\gamma$ ($q^* \to qW$) search required $|\cos\theta^*| < 2/3$ ($|\cos\theta^*| < 0.9$). Also, to reduce backgrounds, the $q^* \to qW$ search required the rapidity boost along the z-axis in getting from the lab to the center of momentum frame to satisfy $|Y_{Boost}| < 1.5$, and required the difference in azimuthal angle between the neutrino and the jet to satisfy $|\Delta\phi_{\nu j}| > 0.4$ radians.

In Fig. 1 and Fig. 2 we present differential cross sections as a function of mass in bins equal to the mass resolution. In Fig. 1 the photon candidate + leading jet mass spectrum is compared with an estimate of the QCD background, coming from a next-to-leading order prediction of prompt photon production [6] multiplied by our independent measurement of the ratio of photon candidates to true photons [7]. The data and QCD background prediction are in good agreement, and there is no compelling evidence for an excited quark signal, which is also shown in Fig. 1 for a few different values of the q^* mass. In Fig. 2 the distribution of the smallest of the two solutions for the W boson + leading jet mass is compared with the predictions of a Monte Carlo and detector simulation for both the QCD background[8, 9] and the excited quark signal [9] separately. Again, the measured mass distribution is in good agreement with the QCD background prediction, and there is no evidence for an excited quark signal. There are two bins within the distribution which have no events; for these we show only the Poisson 1σ error bar rising from 0 to 1.84 events. Only Poisson statistical uncertainties are shown in Fig. 1 and Fig. 2; systematic uncertainties are only used when setting limits. Fig. 1 has been corrected for acceptance and efficiency to allow future comparisons with theory, while Fig. 2 has not been fully corrected, since theoretical predictions of the W + jet mass require a modelling of the significant effects of the detector resolution anyway.

To set a limit on the cross section for excited quark production as a function of excited quark mass, we assumed that the measured mass spectrum came from the sum of an excited quark signal and a QCD background. The predicted signal at mass M from an excited quark of mass M^* was calculated from the theory [1, 10] and then smeared with our detector resolution. For the photon channel this was done both analytically and with a Monte Carlo [11] and detector simulation; both methods included the effect of gluon radiation on our mass definition and gave the same result. Resolution smeared peaks for a few excited quark masses are shown in Fig. 1 and Fig. 2. The predicted QCD background came from a smooth parameterization [12] for the photon channel and a QCD Monte Carlo [8] and detector simulation for the W channel. In each channel separately, we let the normalization of the signal float by multiplying it by a normalization parameter α, and added in the background to obtain the predicted number of events μ_i in each mass bin. Here the mass bins had a fixed width of 5 GeV/c^2 for the photon analysis and 25 GeV/c^2 for the W analysis. For each possible value of M^* we formed the Poisson Likelihood for observing the measured events n_i when μ_i are predicted: $L = \prod(\mu_i^{n_i} e^{-\mu_i})/(n_i!)$. For both the γ and W analysis, this likelihood function was convoluted with Gaussian systematic uncertainties in the parameter α, arising from uncertainties in detector response, acceptance and luminosity. Systematic uncertainties reduced the upper excluded mass value (discussed later) by only 2 GeV/c^2, 6 GeV/c^2 and 15 GeV/c^2 for the γ, W and combined channels respectively. We found the 95% confidence level (CL) limit in the parameter α, α_{Limit}, by solving $[\int_0^{\alpha_{Limit}} L(\alpha)d\alpha]/[\int_0^{\infty} L(\alpha)d\alpha] = 0.95$. Multiplying the total expected cross section for an excited quark of mass M^* by α_{Limit} gives the 95% CL upper limit on the cross section for excited quark production.

In table I we list the 95% CL upper limits and the predicted total q^* cross section. The limits on cross section times branching ratio can be used to set limits on phenomena other than excited quarks assuming the width of the predicted signal is significantly less than our mass resolution. In Fig. 3 we show the 95% CL upper limit on the total excited quark production cross section vs. excited quark mass for the W channel, the photon channel, and the two channels combined (from multiplying the likelihood distributions). These limits use the predicted branching ratios [1, 2, 10]. Since the limits obtained from the W channel are only for 150 GeV/c^2 and above, the combined limit at 80 and 100 GeV/c^2 is from the photon channel alone. Also shown in Fig. 3 is the theoretical prediction for an excited quark signal. The theoretical prediction is above the 95% CL upper limit on the cross section for the mass range $80 < M^* < 460$ GeV/c^2 for $q^* \to q\gamma$, $150 < M^* < 530$ GeV/c^2 for $q^* \to qW$, and $80 < M^* < 540$ GeV/c^2 for both channels combined. Hence, we exclude an excited quark in the mass range $80 < M^* < 540$ GeV/c^2 with 95% CL for coupling $f = f_S = f' \geq 1$. Since the mass limit is sensitive to the choice of coupling, in Fig. 4 we show the regions excluded at 95% CL in the coupling vs. mass plane for the combined channel. Fig. 4 shows that the CDF excluded range extends those from previously reported searches at LEP [13] and UA2 [14], excluding the simplest model of excited quarks for mass $M^* < 540$ GeV/c^2 at 95% CL.

We have searched for excited quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The photon + jet and W + jet mass spectra are in good agreement with QCD background calculations and there is no compelling evidence for a q^* mass resonance. We have presented upper limits on the q^* cross section vs. mass, and exclude the simplest model of excited quarks [1] for mass $80 < M^* < 540$ GeV/c^2 at 95% CL.

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qg, 10.9% for $q^* \to qW$, 3.5(5.1)% for $q^* \to qZ$, and 2.2(0.5)% for $q^* \to q\gamma$.

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	95% CL Upper Limits			Theory
M^* [GeV/c^2]	$\sigma(q^* \to q\gamma)$ [pb]	$\sigma(q^* \to qW)$ [pb]	$\sigma(q^*)$ [pb]	$\sigma(q^*)$ [pb]
80	79.6	–	2.26×10^4	7.55×10^5
100	63.4	–	1.56×10^4	3.16×10^5
150	32.9	206	3.38×10^3	5.72×10^4
200	4.55	87.2	6.93×10^2	1.51×10^4
250	2.80	36.4	3.07×10^2	4.90×10^3
300	1.69	16.3	1.39×10^2	1.81×10^3
350	0.66	9.46	56.1	7.24×10^2
400	0.68	5.35	39.3	3.08×10^2
450	1.04	3.32	39.8	1.36×10^2
500	0.93	3.41	36.9	62.2
550	0.62	3.93	31.0	28.8
600	0.44	4.00	25.4	13.5
650	0.35	3.94	21.9	6.37

Table I: The 95% CL upper limits on the cross section times branching ratio for $q^* \to q\gamma$ (with $|\eta_\gamma| < 0.9$ and $|\cos\theta^*| < 2/3$) in column 2, for $q^* \to qW$ in col. 3, the combined limit on the total q^* production cross section in col. 4, and the predicted [1, 10] value of the total q^* cross section in col. 5.

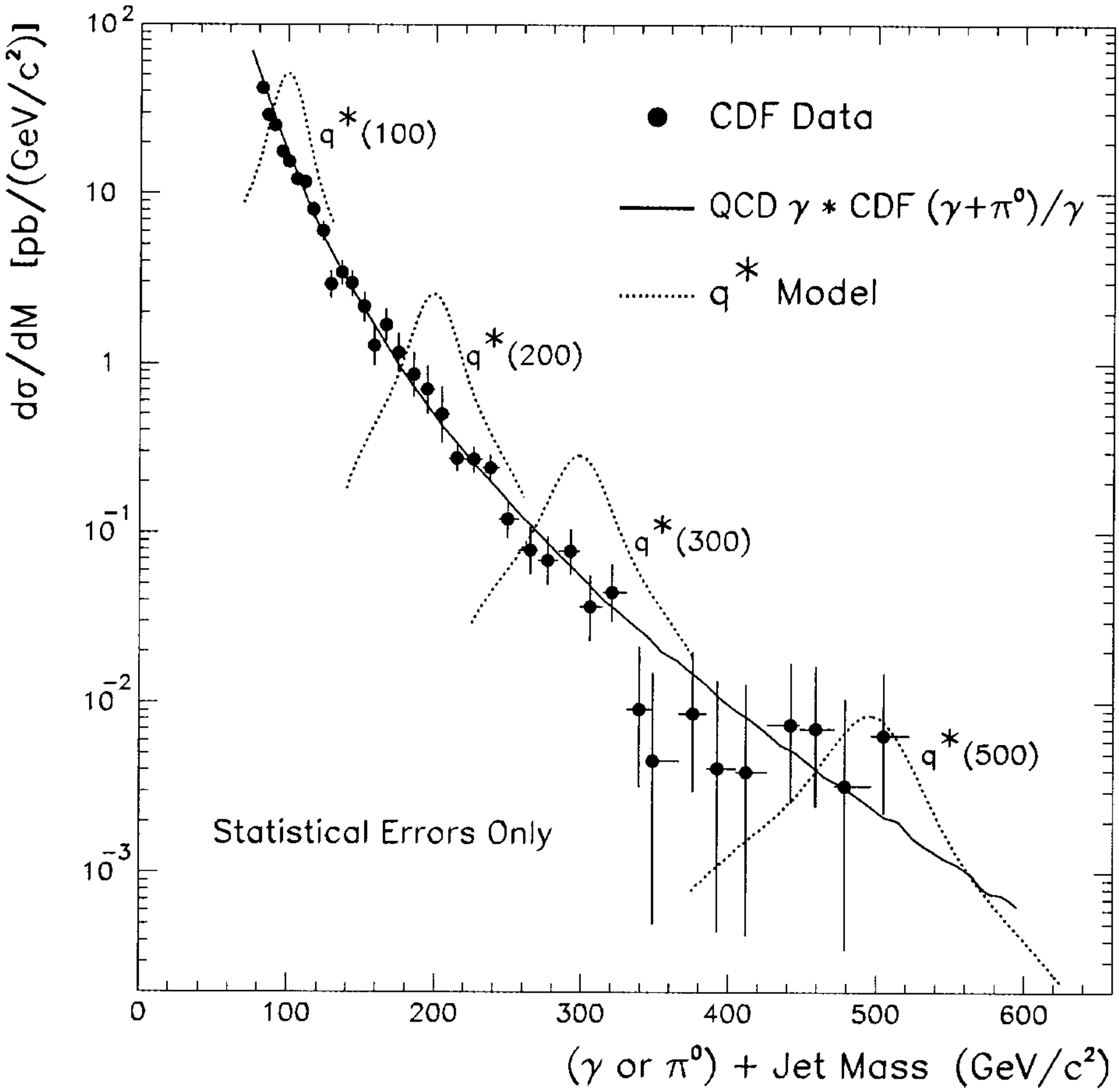

Figure 1: The photon candidate + leading jet invariant mass distribution (points) compared to an estimate of the QCD background (solid curve) and excited quark signal at four different q^* mass values (lotted curves). Corrected for acceptance and efficiency except for the cuts $|\eta_\gamma| < 0.9$ and $|\cos\theta^*| < 2/3$.

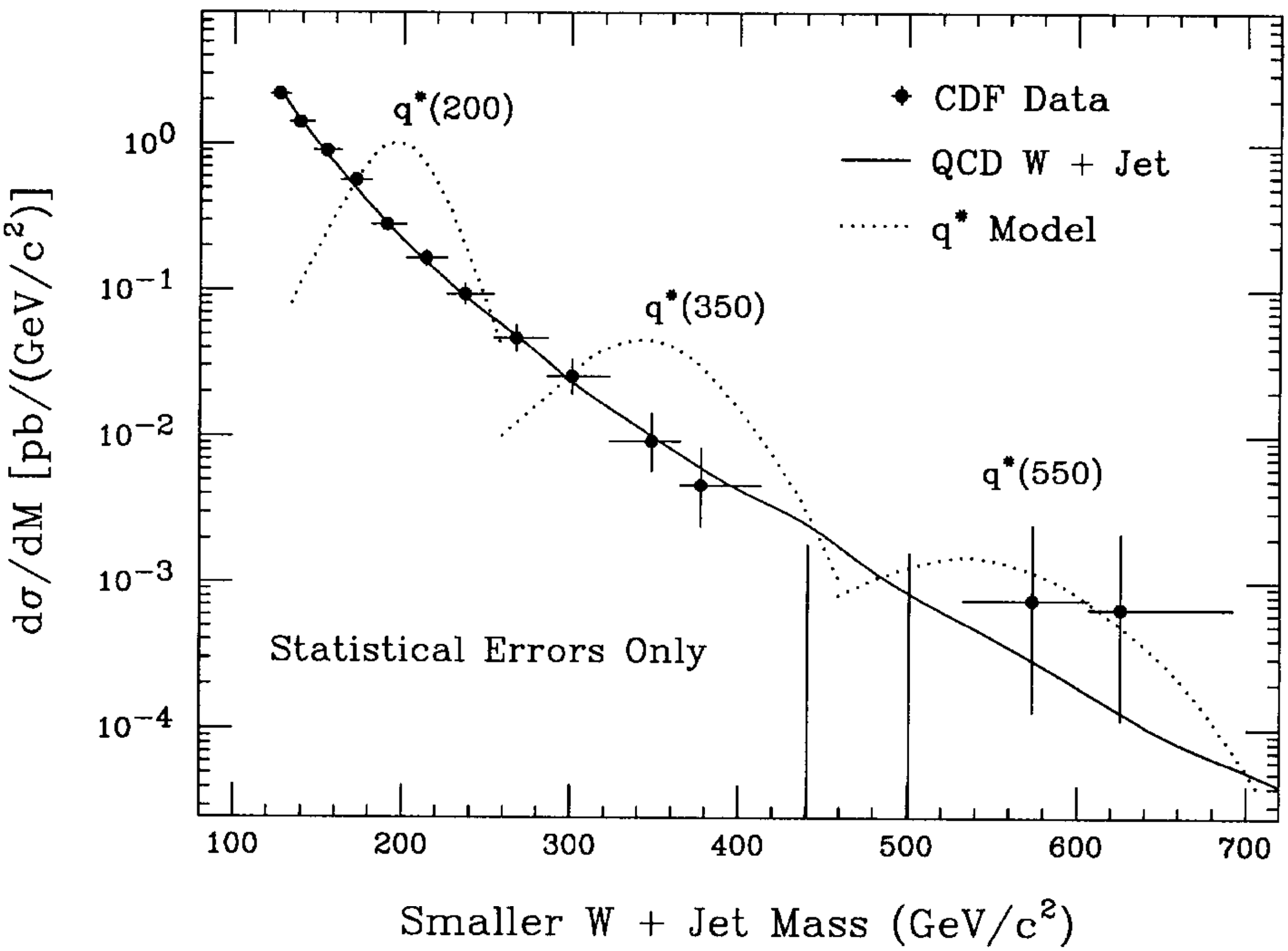

Figure 2: The distribution of the smaller of the two solutions for the W + leading jet invariant mass (points) compared to a Monte Carlo of the QCD background (solid curve) and excited quark signal at three different q^* mass values (dotted curves). Not corrected for acceptance and detector efficiency.

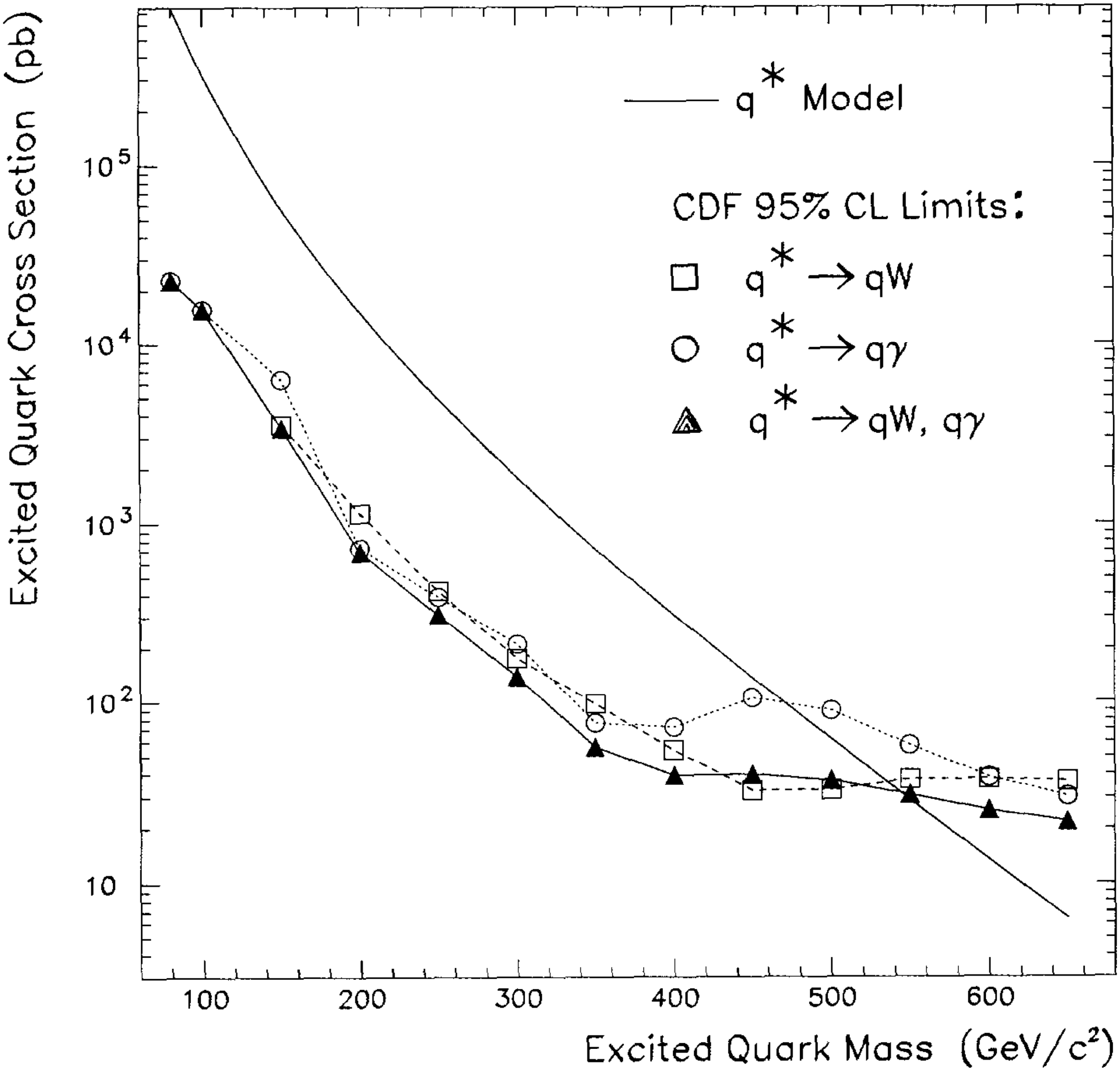

Figure 3: The 95% CL upper limit on the cross section vs. mass from the W channel (squares), the photon channel (circles), and the two channels combined (triangles), is compared to the theoretical prediction (solid curve).

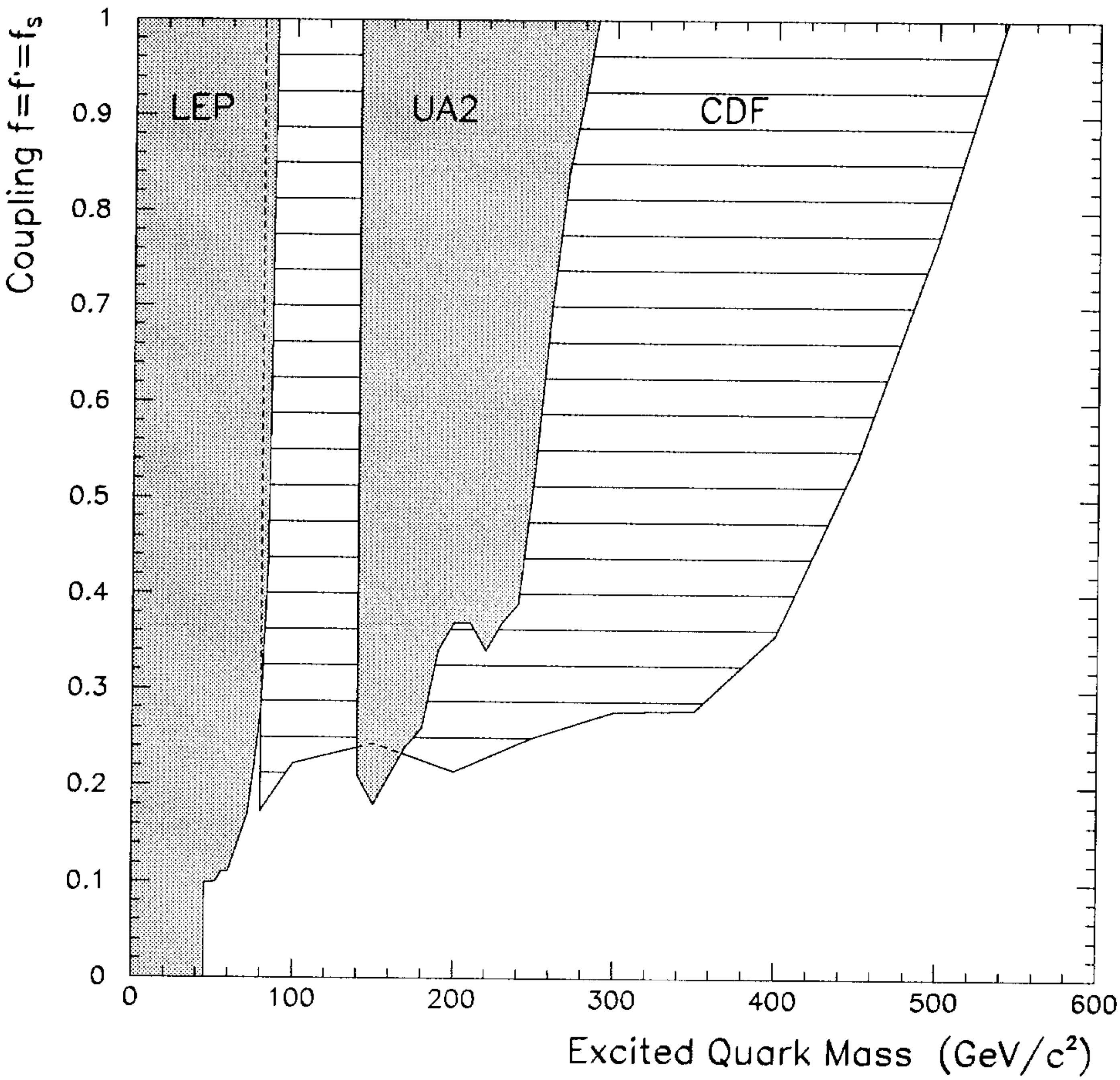

Figure 4: The region of the coupling vs. mass plane excluded at 95% CL by the CDF measurement (hatched region) is compared to the regions excluded by LEP [13] at 95% CL in the $q^* \rightarrow q\gamma, qg$ channels (shaded region) and the region excluded by UA2 [14] at 90% CL in the $q^* \rightarrow qg$ channel (shaded region).